

Droplet Vaporization in a Levitating Acoustic Field

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INTRODUCTION

Combustion experiments using arrays of droplets seek to provide a link between single droplet combustion phenomena and the behavior of complex spray combustion systems. Both single droplet and droplet array studies have been conducted in microgravity to better isolate the droplet interaction phenomena¹⁻³ and eliminate or reduce the effects of buoyancy-induced convection. In most experiments involving droplet arrays, the droplets are supported on fibers to keep them stationary and close together before the combustion event. The presence of the fiber, however, disturbs the combustion process by introducing a source of heat transfer and asymmetry into the configuration. As the number of drops in a droplet array increases, supporting the drops on fibers becomes less practical because of the cumulative effect of the fibers on the combustion process. To eliminate the effect of the fiber, several researchers have conducted microgravity experiments using unsupported droplets. Jackson and Avedisian⁴ investigated single, unsupported drops while Nomura *et al.*⁵ studied droplet clouds formed by a condensation technique.

The overall objective of this research is to extend the study of unsupported drops by investigating the combustion of well-characterized drop clusters in a microgravity environment. Direct experimental observations and measurements of the combustion of droplet clusters would provide unique experimental data for the verification and improvement of spray combustion models. In this work, the formation of drop clusters is precisely controlled using an acoustic levitation system so that dilute, as well as dense clusters can be created and stabilized before combustion in microgravity is begun.

While the low-gravity test facility is being completed, tests have been conducted in 1-g to characterize the effect of the acoustic field on the vaporization of single and multiple droplets. This is important because in the combustion experiment, the droplets will be formed and levitated prior to ignition. Therefore, the droplets will begin to vaporize in the acoustic field thus forming the “initial conditions” for the combustion process. Understanding droplet vaporization in the acoustic field of this levitator is a necessary step that will help to interpret the experimental results obtained in low-gravity.

EXPERIMENTAL METHODS

The acoustic levitator, shown in Fig. 1, is a single-axis driver assembly consisting of two piezoelectric transducers in a sandwich configuration similar to that developed by Cao *et al.*⁶ Aluminum transmitter blocks are placed on both sides of the sandwich transducer and sized to create a plane standing wave in the material when oscillating at 20 kHz. A titanium acoustic horn is coupled to the forward transmitter to amplify the transducer displacement. The tip of the horn is 29 mm in diameter and directs the acoustic wave towards a concave reflector (50-mm diameter). The reflector focuses the acoustic pressure field to produce an axially- and radially-varying pressure field between the driver and reflector.

The droplet evaporation tests were conducted by first producing an acoustic field and then dispensing a droplet to the end of a 90-micron hypodermic needle from a 0.1 ml syringe. Single droplets were simply pulled off the needle by the acoustic field as the needle was

withdrawn. Multiple droplets were produced by rapidly moving the reflector up approximately 2 mm and returning it to its original position. The disturbance in the acoustic field broke up the parent drop into a number of smaller droplets that were then captured and stabilized in the acoustic antinode. The droplets are imaged through a window in the reflector using a CCD camera and recorded on video tape. The time history of the diameter of the droplet (or droplets) is determined by first digitizing the video and then analyzing sequential images using image analysis software.

VAPORIZATION IN ONE-G

As in several other microgravity investigations, methanol has been used in our initial tests of the acoustic levitator/droplet generator system.^{1,2} The first tests were to determine the effect of the acoustic field on droplet vaporization rate for methanol. Table 1 shows the measured vaporization rate for an isolated methanol droplet at different sound pressure levels (SPL). The evaporation rate was found to be relatively independent of the strength of the acoustic field, at least for the levels used in this experiment. Also, the vaporization rate compares very well to the theoretical value for diffusion-controlled, quasi-steady droplet evaporation calculated to be 0.00331 mm²/s. Seaver *et al.*⁷ and Tian and Apfel⁸ used acoustic fields similar in strength to those used in this experiment and drew similar conclusions. Yarin *et al.*⁹ evaluated droplet vaporization at higher SPL (160 dB and above) and found the effect to be significant. Although stronger fields could be applied, the strength of the field was maintained at the minimum required to levitate the droplets.

Table 1. Isolated Droplet Vaporization at Varying Sound Pressure Level

SPL (dB)	d ₀ (mm)	-K (mm ² /s)
119	0.463	0.00352
123	0.476	0.00354
128.3	0.562	0.00400

Tests were also conducted using ethanol droplets to confirm consistent behavior with drops having a different composition. Figure 2 shows the vaporization rate data obtained for isolated ethanol and methanol drops. As expected, ethanol evaporates at a faster rate and, as shown in the legend, both yield values of the vaporization rate constant, K, that compare well with that predicted by the d²-law. Similar experiments were conducted using two- and three-droplet clusters to develop and evaluate procedures before advancing to clusters having a greater number of droplets.

Before discussing the experimental results for multiple droplet conditions, the theoretical model to which the results are compared will be presented. A number of simplified theories of droplet vaporization and combustion have been developed to study multiple droplet effects.¹⁰⁻¹³ Several investigations using detailed numerical simulations have also been conducted.¹⁴⁻¹⁶ Labowsky¹⁰ applied the method of images to calculate the effect of arrays of up to seven equally-sized interacting drops on combustion and evaporation process. He found that the burning rate was decreased by approximately 10% when the drops were separated by 20 droplet diameters and up to 30% as the spacing became less than 5 diameters. A more detailed, three-dimensional analysis of Kim *et al.*¹⁵ reached a similar conclusion. The Point Source Method (PSM) developed by Annamalai and Ryan¹⁷ determines the mass loss rate of interacting drops by treating each droplet as a point mass source and heat sink, and evaluates the steady-state mass loss of arrays of

interacting drops in a quiescent atmosphere with $Le = 1$ and $Sh=2$. For arrays up to 5 drops, results from the PSM have been shown to be in excellent agreement with the results obtained through the exact methods developed by Labowsky¹⁰ and Brzustowski *et al.*¹¹ One of the primary reasons for using the PSM method for the initial comparisons with our data is that, once the appropriate equations are developed, experimentally-measured droplet diameters and spacing can be input. This yields correction factors for the vaporization rate relative to the isolated droplet vaporization rate for the unequally-sized and spaced droplets found in an experiment.

Table 2 shows the results of the PSM method for a typical three-droplet cluster. The vaporization rate of the larger droplet is shown to compare fairly well with the predictions of the PSM. The rates for the two smaller droplets are substantially less than predicted. Because of the stability of the cluster, we know all three droplets were in the same pressure well and, therefore, were exposed to relatively the same conditions. Yarin *et al.*⁹ indicated that without external blowing, the accumulation of vapor in the pressure well could reduce the vaporization rate. Given that convection by acoustic streaming would be to increase the vaporization rate and the SPL for this experiment is well below the levels at which these effects are observed, vapor accumulation appears to be a plausible explanation. Other data sets are being analyzed to further evaluate these observations. Also, numerical simulations of the experimental configurations are underway using a modified version of the Fire Dynamics Simulator (FDS) code¹⁸ to investigate this phenomenon in more detail.

Table 2. Comparisons for Three-Droplet Ethanol Cluster

Diameter (mm)	Droplet Spacing (mm)			m''/m''_{iso}	
	1 - 2	1 - 3	2 - 3	Experiment	PSM
0.512				0.860	0.884
0.476	2.96	2.52	2.41	0.672	0.875
0.293				0.281	0.822

SUMMARY

A single axis acoustic levitator has been designed and constructed. The design of the acoustic levitator provides both a vertical and lateral positioning force on the droplets and stable clusters containing between 2 and 20 drops have been generated. Results have shown that isolated droplet vaporization in a resonant acoustic field at 1-g are consistent with those of previous researchers. Current work consists of comparing vaporization rates from droplets within a cluster to predictions of the Point Source Method. Numerical simulations using the Fire Dynamic Simulator (FDS) have also begun. Meanwhile, fabrication of the drop tower test facility is progressing and should be ready for testing during the summer of 2003.

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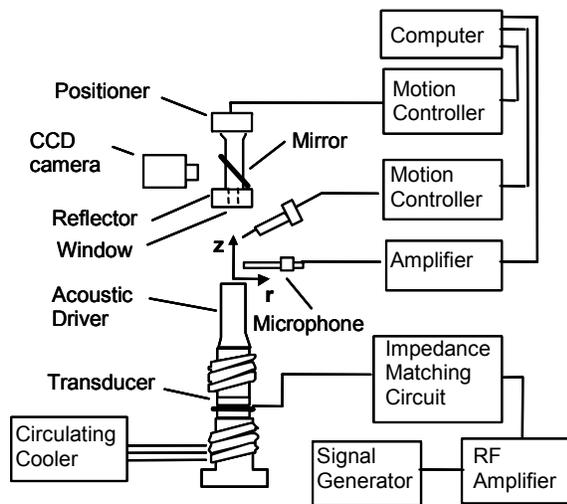


Figure 1. Droplet levitation apparatus

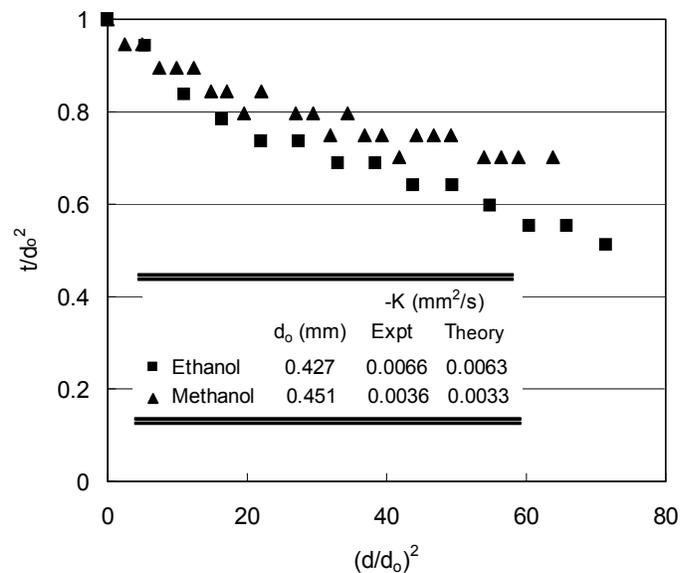


Figure 2. Comparison of ethanol and methanol evaporation